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DEVELOPMENT AND FABRICATION OF MATCHED LONGITUDINAL ACOUSTIC WAVE TRANSDUCERS

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Prepared for

Massachusetts Institute of Technology
Lincoln Laboratory

Final Report

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ILLUSTRATIONS

ABSTRACT

The design and fabrication of a matched pair of 4 μs, wide bandwidth delay devices is described with operation over a 500 MHz bandwidth centered at 1.7 GHz. Design techniques are discussed which allow relatively low insertion loss (35 dB) with extremely flat frequency response (±0.5 dB) and superior TTS (above 45 dB). The magnitude of transmission phase ripple relative to linear phase is considered both theoretically and experimentally. Construction in a constant temperature oven for phase-stable operation is described. The characteristics of devices obtained in quantity production are estimated.

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Chief, Lincoln Laboratory Project Office

I. INTRODUCTION

The purpose of this program was to develop a matched pair of wideband delay lines operating in L-band with exceptionally flat phase and insertion loss characteristics. Since the properties of the acoustic delay medium vary rather slowly, one of the major problems that had to be solved was the design and fabrication of matched electro-acoustic transducers having low loss wideband response. To attain the exceptionally flat phase response desired, the development of sophisticated techniques for suppressing all spurious signals was also required.

The over-all delay device goals for this project which incorporate the above characteristics are outlined below:

Center Frequency	1.7 GHz
Bandwidth	500 MHz
Amplitude Ripple	±0.5 dB
Phase Ripple	±2 degrees
Delay	4 ±0.05 μsec
Matching Delay of Pair	±1 nanosecond
Insertion Loss	30 dB (plus attenuator or isolation loss necessary for desired VSWR)
Triple-Travel Suppression	45 dB
Feedthrough Suppression with respect to output pulse	60 dB
Input and Output Impedance	50 ohms
Input and Output VSWR	<1.3:1 over the required bandwidth
Operating Temperature	Not specified, but variation limited to ±5°C
Phase Delay Stability with oven temperature	Stable to ±1 electrical degree for operating temperature

This report gives a detailed summary of the device performance for the matched delay lines in all of these categories. First, insertion loss characteristics are discussed and general techniques for achieving the exceptionally smooth passband are explained. Next, the methods used in achieving exceptional spurious suppression are described. Finally, a summary of total device performance is given and an evaluation of future device characteristics outlined with respect to quantity delivery of matched delay devices. This outline includes device characteristic trade-offs for various quantities of matched devices.

II. DELAY LINE INSERTION LOSS AND VSWR

A principal goal in this program is the attainment of exceptionally smooth delay line insertion loss response over a broad operating bandwidth. The design specification of 500 MHz bandwidth centered at 1.7 GHz with ±0.5 dB amplitude ripple required the development of new techniques in the design and fabrication of thin-film electro-acoustic transducers and associated coupling networks.

A transducer configuration with gold electrode layers at thickness 0.1 μm or less was found most practical for this broadband application. Essentially identical film thicknesses were used for transducers at each delay line port.

Top electrode, Au; 0.07μm
Piezo layer ZnO, 1.25μ
Counter-electrode Au, 0.07μm

A matrix of top electrode dots was provided on each transducer and the optimum pair of dots for each delay line was selected for best insertion loss and TTS characteristics. Figure 1 shows the film deposition sequence for this delay line. Contact to this selected pair of dots was achieved by thermocompression bonding of 2-mil wires.

The exact transducers used for the final devices in this project were not power tested. However, transducers of similar size and thickness have been tested and will typically handle at least 10 watts peak or 100 mW CW. The major breakdown mechanism is believed to be a result of either film impurities (for example, gold film surface irregularities or zinc oxide pin holes) or a normal dielectric breakdown process. Both factors are highly dependent on film thickness and processing cleanliness. The result of a breakdown is observed by a shorted (low resistance) transducer. With large CW power, heat dissipation also becomes a contributory factor.

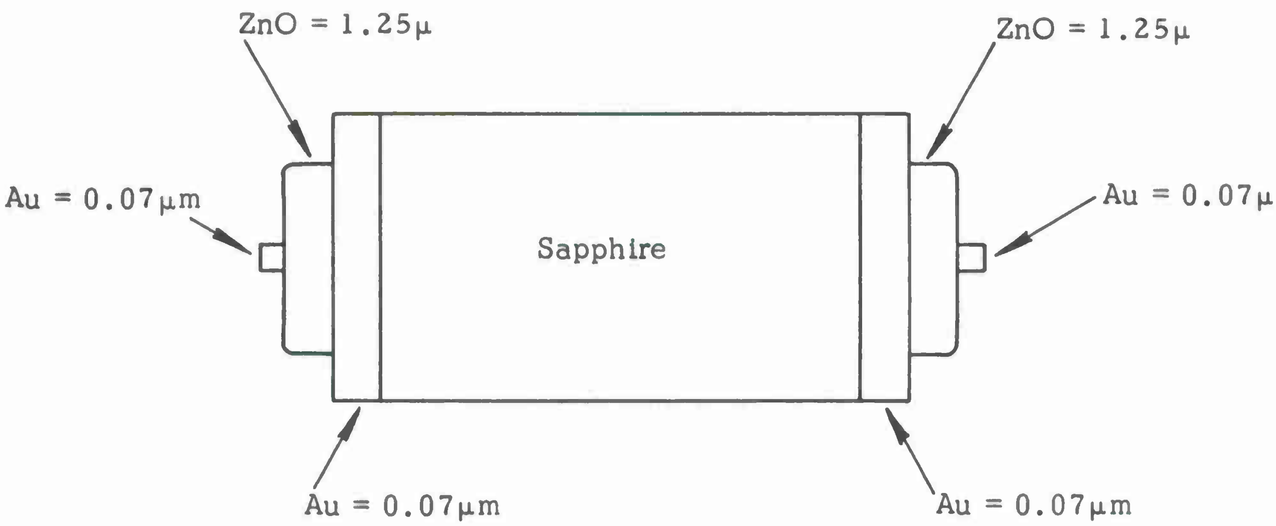

Figure 1. Final delay line configuration.

The high-Q behavior of the input impedance of thin-film transducers presents a difficult design problem where both low insertion loss and broadband operation are desired. From theoretical considerations[1,2] and from studies carried out during this program[3], it is clear that microwave networks can be designed which allow broadband operation of even relatively high Q transducers. Such networks fall into the class of the reflection loss filter[4].

We have discovered that a quarter-wavelength transformer with the proper choice of transformer impedance Z_I can yield extremely wideband response. Calculations demonstrating the range of responses available are shown in Figure 2. Small values of Z_I produce a loss curve with a maximum at f_o and two minimums placed symmetrically about f_o, while large values of Z_I produce a single-minimum response. Most important, however, is the fact that special intermediate values of Z_I yield an extremely wideband, low-ripple response. This happens because at a special value of transformer impedance the plot of the series-resonant impedance $Z_a(f)$ on a Smith chart forms a nearly circular loop about the center of the chart indicating that the magnitude of the reflection coefficient is approximately a constant over a wide frequency range.

Since these networks provide uniform coupling by reflecting some power at all frequencies, the input VSWR is always greater than one. Further, the higher the load Q, the larger the average network VSWR must be for a given design bandwidth. Thus, in order to achieve both broad bandwidth and low VSWR, input attenuators or isolators are needed. With a design specification of 30 dB insertion loss and VSWR of 1.3, it became apparent early in this program that a transducer and network design satisfying all of these requirements simultaneously would be extremely difficult, if not impossible.

Since smooth response and low input VSWR were deemed of utmost importance, it was decided that, if necessary, an insertion loss above 30 dB would be accepted, so that all other requirements could be satisfied. It was found that low VSWR, and insertion losses close to 30 dB could be attained if low

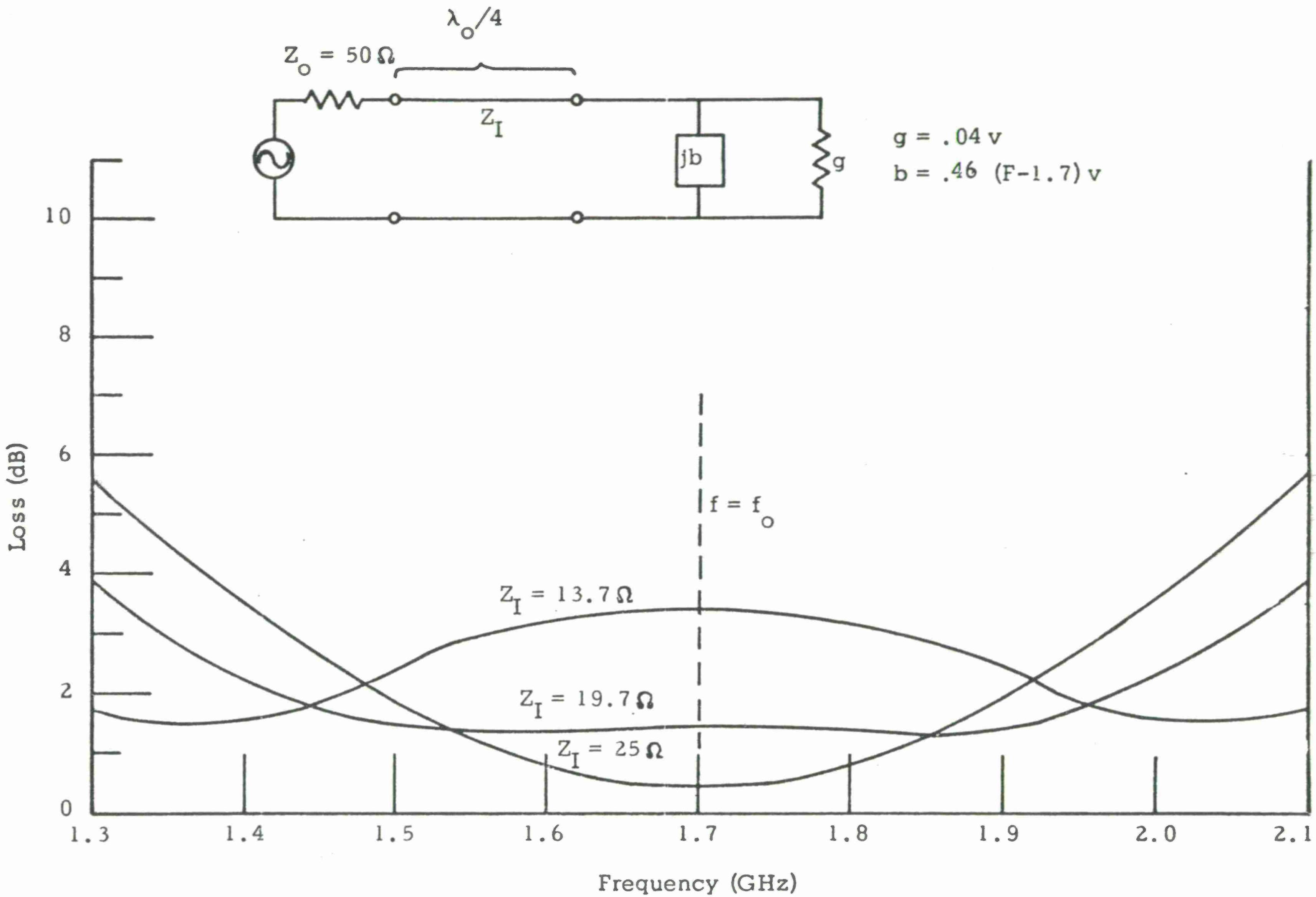

Figure 2. Wideband response of a single inverter stage.

loss isolators were used at both input and output of the delay device. However, as described further in Section IV, the isolators cause additional phase ripple which is undesirable. The final design chosen for the present program makes use of an attenuator at the delay line input and an isolator at the output. This compromise satisfies the amplitude and phase response requirements with a minimum increase in insertion loss.

As a result of the diagnostic transducer studies carried out at the beginning of this program[3], the following straightforward transducer and coupling network design procedure has been developed:

- Characterize the transducer impedance Q, and insertion versus frequency without the use of a coupling network.
- Design the coupling network impedance based on the transducer Q and impedance level.
- Add a transmission attenuator or isolator to achieve the required VSWR.

Much of the success of the above procedure is owed to the high yield and reproducible system of thin-film ZnO transducer fabrication developed at Teledyne MEC on other contracts.

Figure 3 shows the insertion loss for the final matched pair of delay lines fabricated in this program. The data shown were taken when the delay lines were first installed in the microwave package; i.e., before the coupling networks and attenuator or isolator were installed. Without the presence of the coupling network the insertion loss response is controlled by the transducer Q. Thus, the 0.5 dB bandwidth is only 50 to 100 MHz. However, we note that the minimum loss for the two delay lines is accurately centered at the 1.7 GHz design frequency with minimum values less than 26 dB, indicating that the basic transducer design is quite efficient at the design frequency. Figure 1 also shows the level of TTS of these delay lines as initially installed, before the optimization

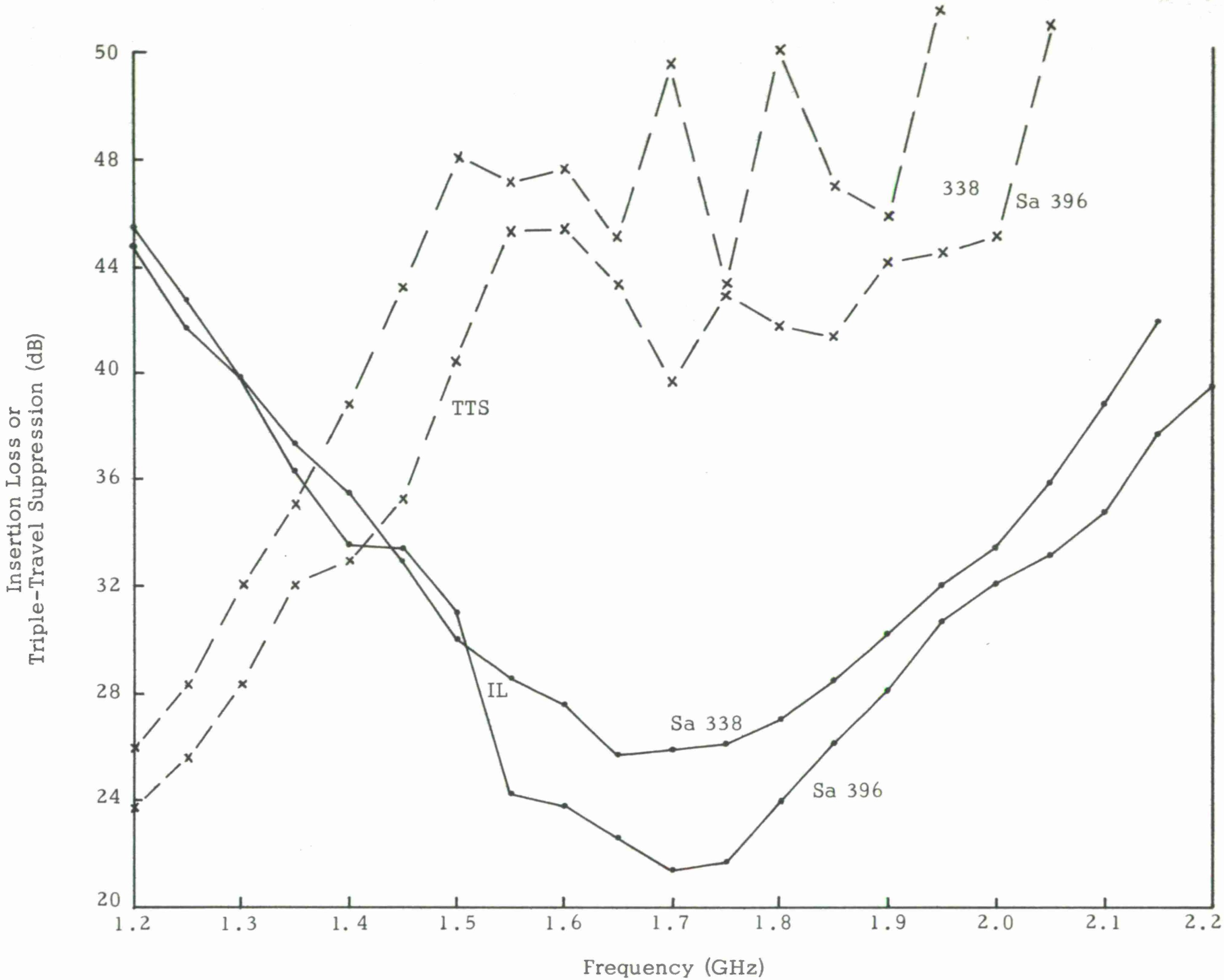

Figure 3. Insertion loss and triple-travel suppression of delay devices Sa 338 and Sa 396 before the coupling network and attenuators or isolators were installed.

technique described in Section III is carried out. As seen in Figure 3, the average characteristics of the two delay lines have a degree of uniformity which is considered excellent at the present state of the art.

Figures 4 and 5 show the final insertion loss and VSWR characteristics for the matched delay lines after the matching networks and attenuator/isolators were added. These detailed point-by-point measurements show that the desired insertion loss response, flat to within ±0.5 dB was attained. A 6-dB attenuator was used at the input of each device while a special order isolator[5] was installed at the output to limit the VSWR. The maximum VSWR seen for delay line Sa 338 (Figure 4) is 1.5 and for Sa 396 (Figure 5) is 1.4. These maximum values are slightly above the 1.3 design goal, but can be reduced to 1.3 by adding an additional 2 dB attenuation.

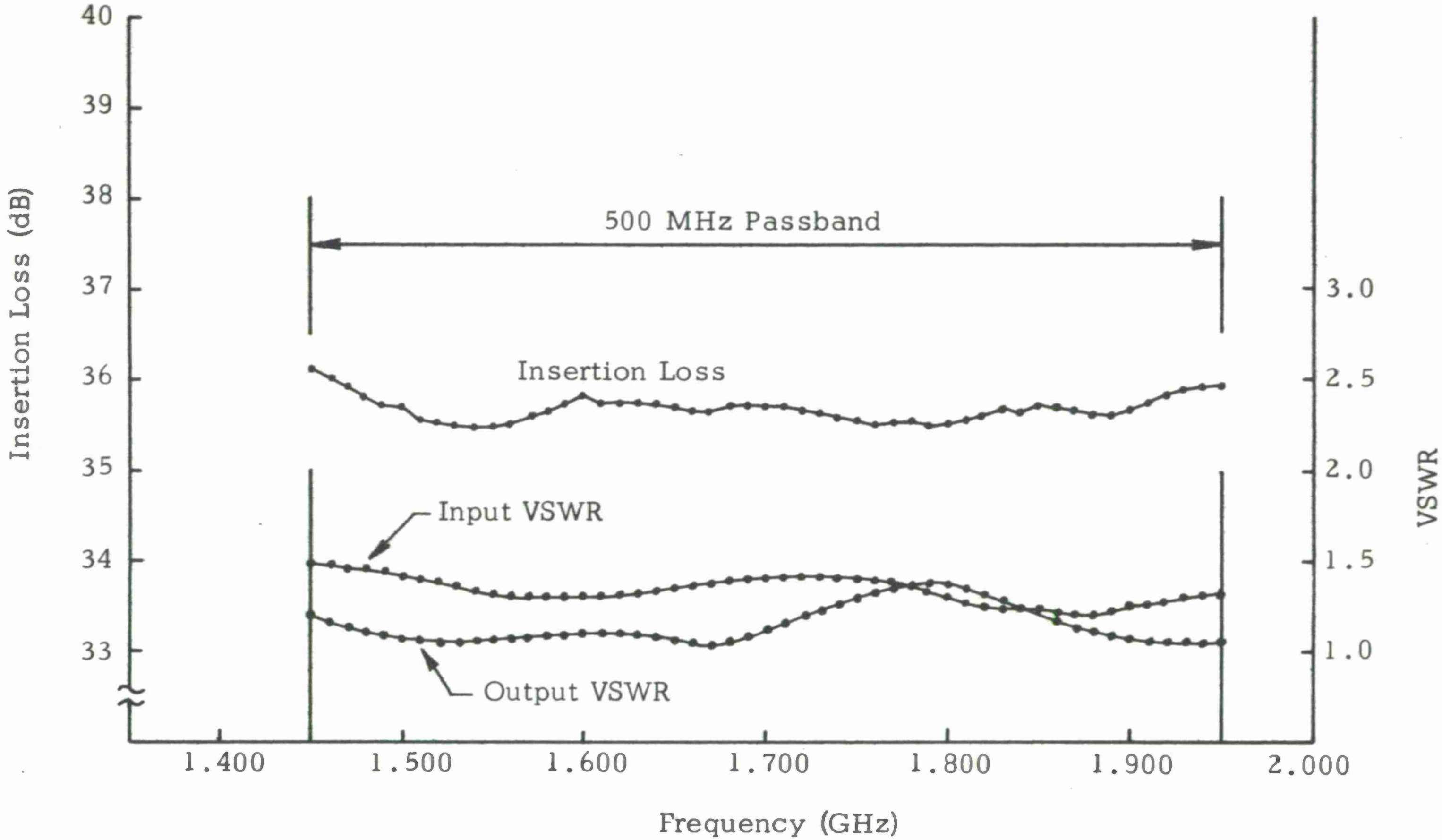

Figure 4. Final insertion loss and VSWR characteristics for Sa 338.

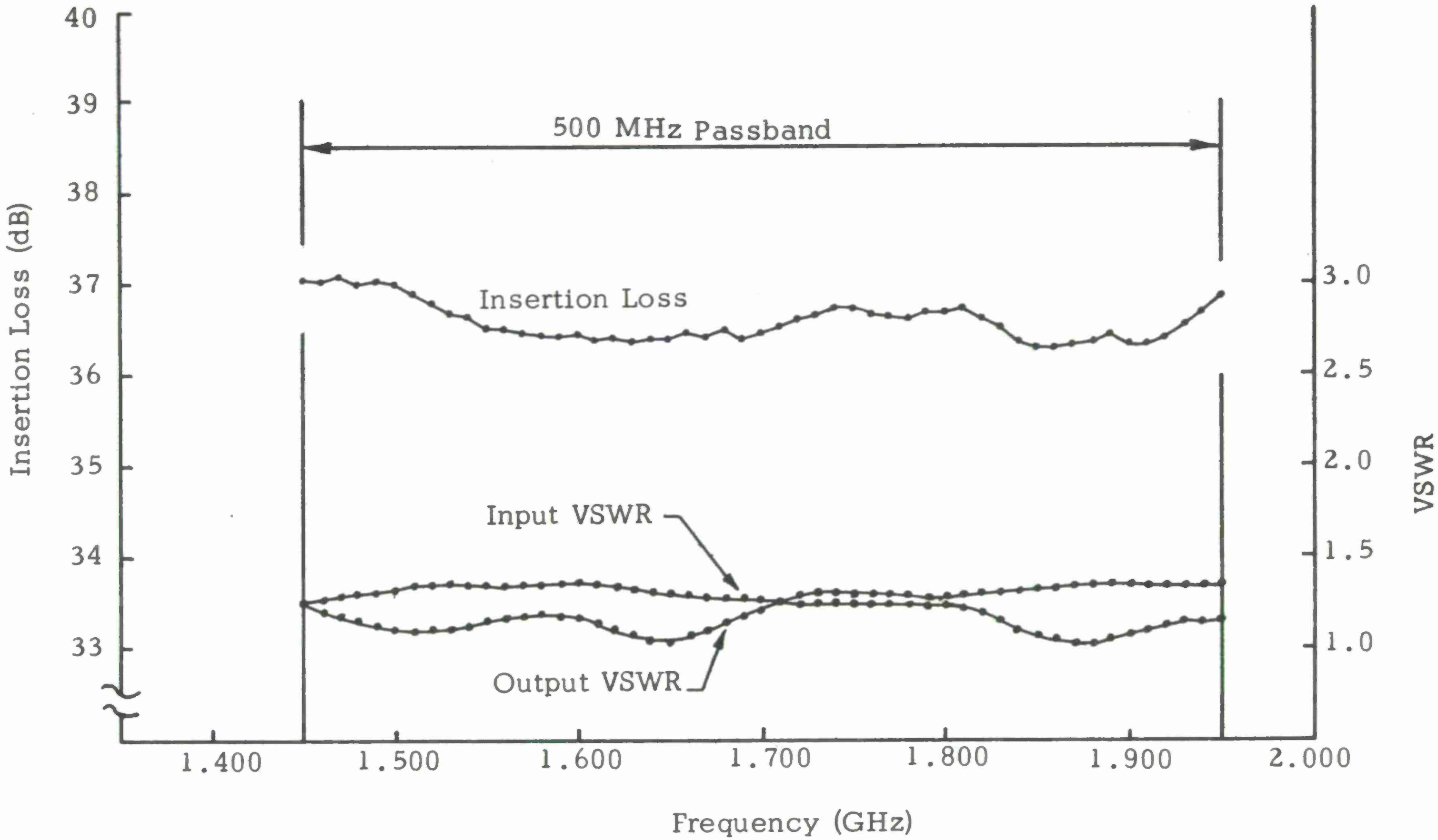

Figure 5. Final insertion loss and VSWR characteristics for Sa 396.

III. TRIPLE-TRAVEL SUPPRESSION

The attainment of TTS levels greater than 20 dB usually requires that a variety of spurious suppression techniques be employed. Where TTS levels of 45 dB or more are desired, as in the matched delay devices under discussion, these techniques must become quite sophisticated. In the initial phase of this program we investigated the level of TTS available due to (1) delay media propagation loss, (2) transducer acoustic power absorption and, (3) aperture diffraction due to finite transducer size. Since a 1 dB increase in these types of loss usually gives a 2 dB increase in TTS, we attempted to make each optimally large without deleteriously increasing the device insertion loss. The sapphire delay medium was chosen for its reproducible delay and transducer substrate qualities. The available propagation loss with this high quality media (1.2 dB for 4 μs delay) is relatively low. The wideband transducer design utilizes a reflection filter approach to gain bandwidth, as discussed in Section II. Thus, the transducer does not appreciably absorb acoustic power. Finally, there are definite limits on the maximum diffraction loss obtainable since an increase in diffraction loss means a decrease in transducer size which leads to an undesirable narrow band transducer response. We have concluded that TTS levels of only 20 dB or less are available in 4 μs L-band delay line using the above three techniques. To gain additional increase in TTS we have investigated the further techniques of (4) using a slight bevel angle between the delay line end faces and (5) adding series acoustic loss to provide increased propagation loss. Technique (4) makes use of the antenna-like diffraction pattern of the transducer and provides just the right amount of non-collinearity of the reflected acoustic beam such that the triple-travel signal arrives at the angle corresponding to the acoustic null between the major spatial beam and the first sidelobe[6]. This technique alone can add 10 to 15 dB to the TTS level but is not quite sufficient to achieve 45 dB. Technique (5) is then used to provide the final increment of needed TTS.

Figures 6 and 7 illustrate the final TTS levels achieved in the matched delay devices, Sa 338 and Sa 396. For the final design the input transducer face was accurately (within ±5 minutes) aligned perpendicularly to the sapphire rod C-axis. The output face was oriented on the bevel angle 43.2 minutes away from perpendicular. The data given in Figures 6 and 7 shows that TTS well above 40 dB can be achieved over the desired 500 MHz L-band passband. One device, Sa 338 (Figure 4) has TTS above 45 dB over the entire bandwidth. The second device, Sa 396 (Figure 5) is almost as good, with TTS above 45 dB over the range 1.45 to 1.7 and above 43 dB from 1.7 to 2.0 GHz.

Special care was used in measuring and cutting the sapphire delay media so that accurately matched delay times could be achieved. The original four test rods were fabricated equal in length within ±0.0002 inch corresponding to a matched delay within 3 nsec. The final matched pair has a delay time of 3.95 μsec.

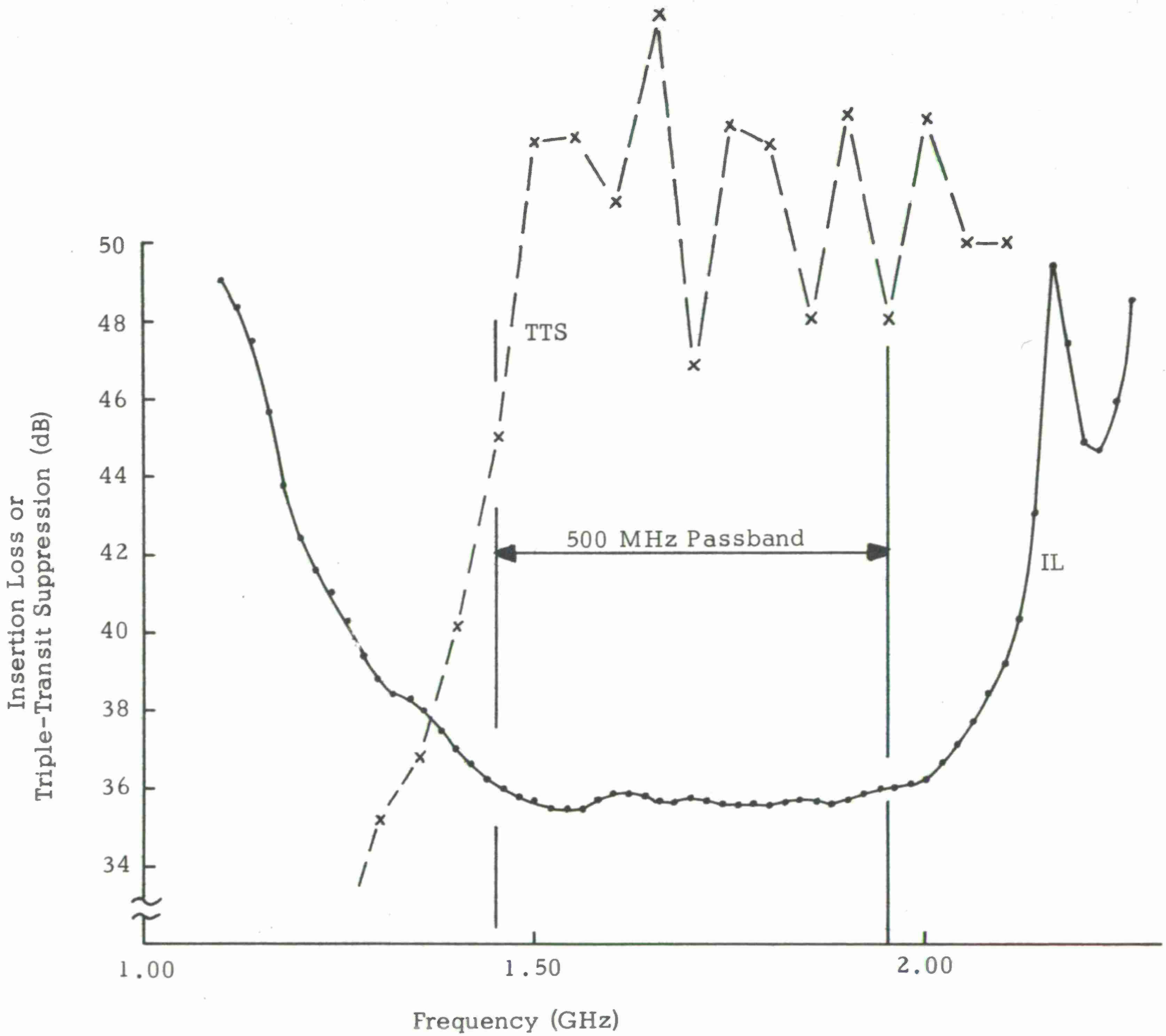

Figure 6. Final insertion loss and triple-transit suppression characteristics for Sa 338.

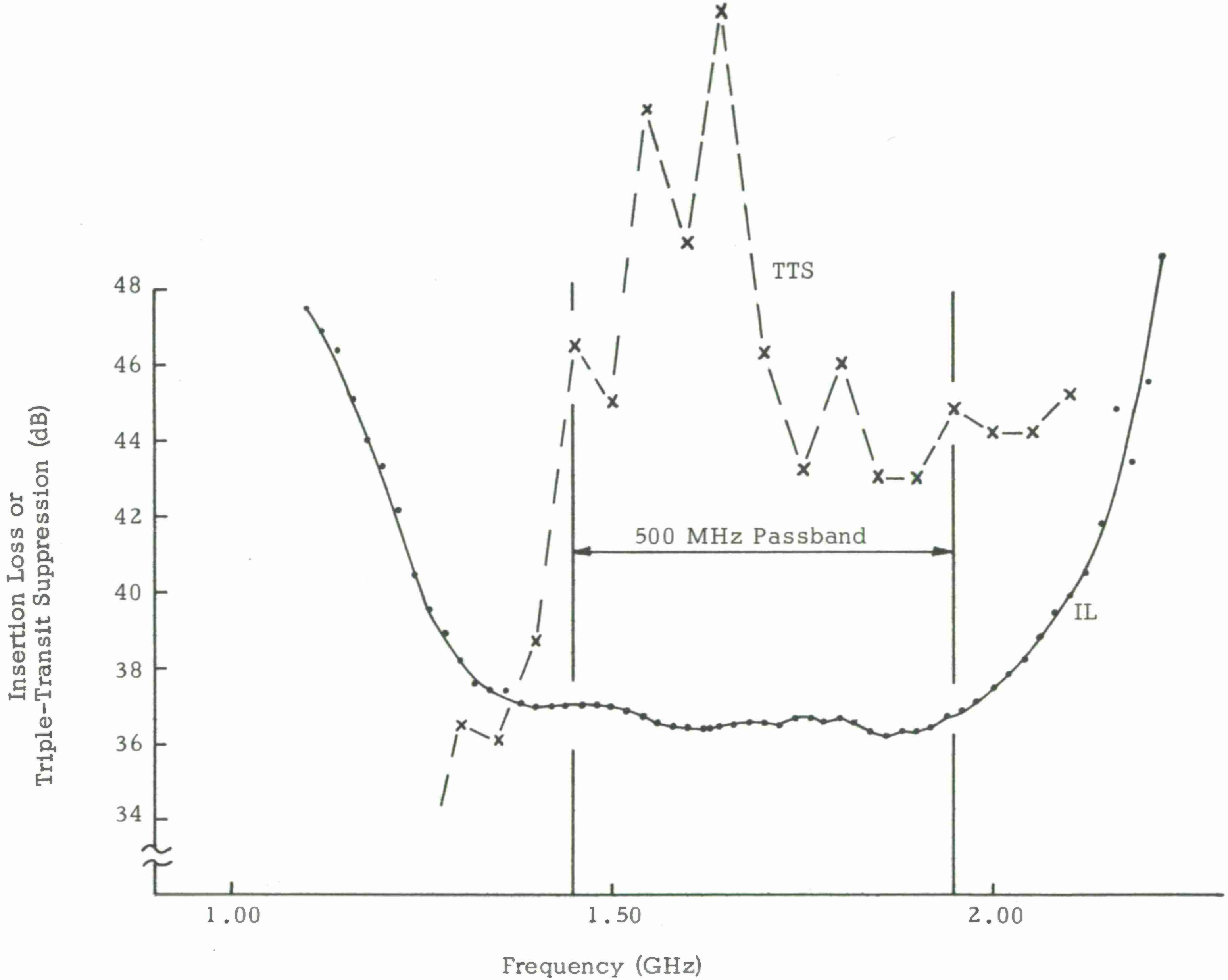

Figure 7. Final insertion loss and triple-transit suppression characteristics for Sa 396.

IV. PHASE RIPPLE

A further requirement imposed upon the matched delay devices is that their transmission phase characteristic should be highly linear with a phase ripple no larger than ±2 degrees. There are a number of sources that can contribute to the over-all phase ripple:

- attenuator/isolator used to limit VSWR
- transducer coupling networks
- transducer transmission phase characteristic
- multiple reflections of the signal within the delay line

Experimentally, we have separately measured the phase response of the attenuators, isolators and individual delay lines as well as the over-all response of the completed units. All such tests have been performed with a Hewlett-Packard 8410 Network Analyzer. Figure 8 shows the measured phase ripple response for delay device Sa 338. The original data was obtained in transmission phase form; a least-squares-fit of the data was used in subtracting out the linear phase component, yielding the ripple data shown in Figure 8. At these insertion loss levels the Hewlett-Packard Network Analyzer has a limiting accuracy of ±0.6 degrees. Accounting for this average measurement error, the ripple is seen to be less than ±2.5 degrees. We shall now briefly consider each of the sources that lead to this phase characteristic.

The attenuators were found to have an extremely linear phase response with a ripple possibility much smaller than ±0.6 degrees. The isolators produced much more ripple, as may be seen by the data shown in Figure 9. However, these units were designed by the vendor[5] to have minimum ripple over the desired 500 MHz bandwidth. Isolator No. 2 has the largest ripple ±1.25 degrees over the range 1.45 to 1.95 GHz.

In general, the phase ripple of a passive device is proportional to the slope versus frequency of its insertion loss characteristic[7]. Thus, if the isolation loss is very smooth, the phase ripple will be small. The above theorem has

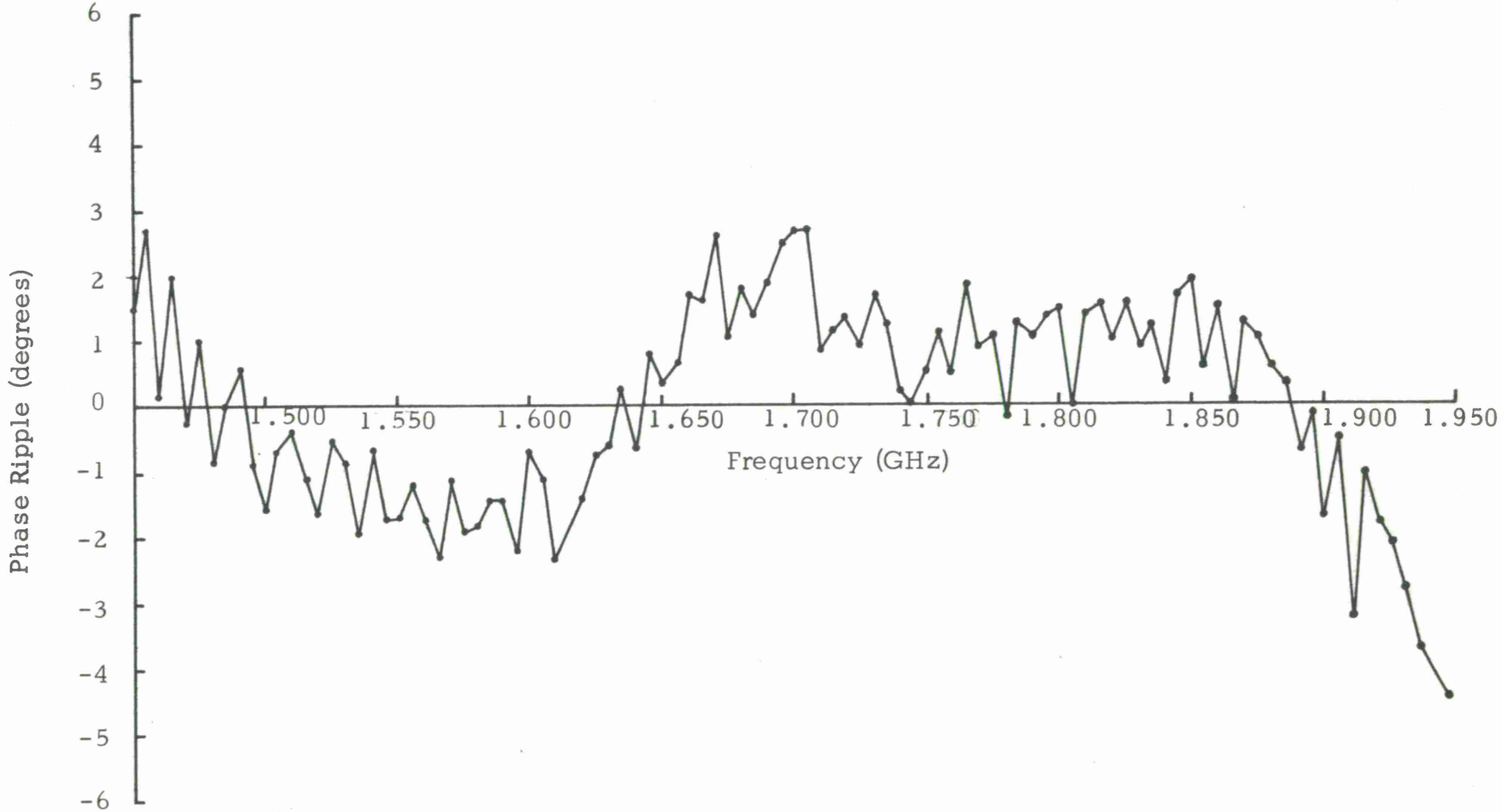

Figure 8. Phase ripple for Sa 338. Measurement accuracy ±0.6 degrees.

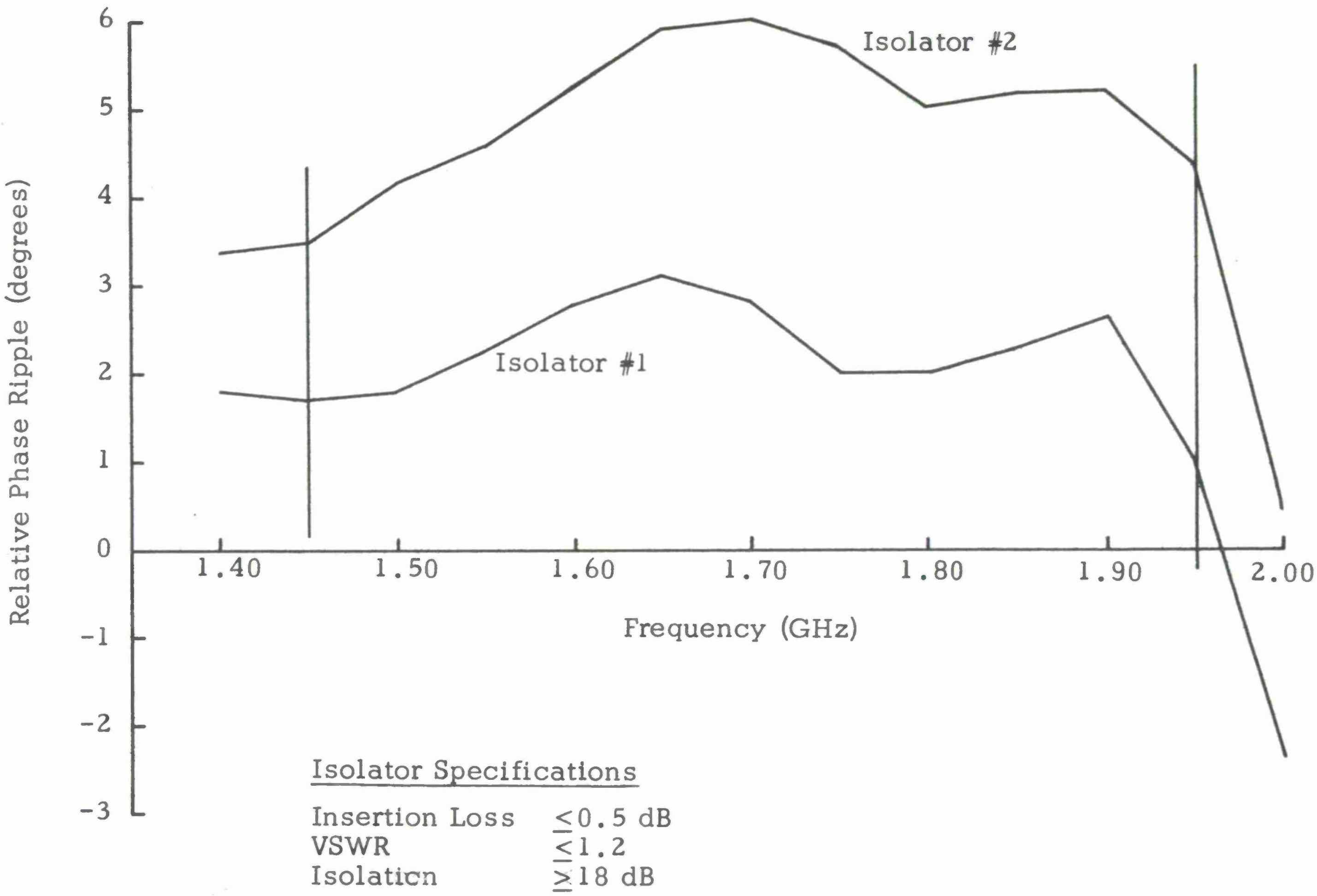

Figure 9. Phase response and isolator characteristics for isolators used on output of each delay line.

proved consistent with the phase-insertion loss curves obtained for the attenuators and isolators described above. The same statement also applies to the wideband coupling network designed for smooth coupling loss. Figure 10 compares the measured phase ripple data for delay device Sa 338 with the calculated phase ripple due to couplng networks at both input and output. The sinusoidal phase response of the networks crosses zero at a frequency slightly above the 1.7 GHz design frequency in accordance with the measured transducer-network response of the completed delay device. We conclude from Figure 10 that a ripple magnitude of about two degrees could be caused by the coupling networks.

Phase ripple caused by the transducer transmission phase response was not directly calculated since we have seen in earlier calculations that the transducer acoustic amplitude response is flat to better than ±0.1 dB. The corresponding phase ripple should thus be much less than seen for the coupling networks[3, 7].

Multiple reflections of acoustic signals within the delay line also cause phase ripple since these reflections add vectorially at the device output. In practice it is only the triple travel reflection which is of importance. We can relate the relative amplitude (A) of this triple-travel signal to the level of TTS in dB by the expression

$$A = 10^{-TTS/20} .$$

Thus, A is 0.1 for 20 dB TTS, 0.01 for 40 dB TTS and so on. Where the TTS is above 20 dB the maximum phase ripple due to TT signals is given by

$$\Delta\varphi = (180/\pi)\, A$$

in degrees. For TTS above 40 dB the added phase ripple would be less than ±0.6 degres and therefore would not be measurable with available equipment. Earlier experiments[8] with delay devices having TTS in the 20 dB range have shown that the phase ripple due to triple-travel signals may be accurately predicted.

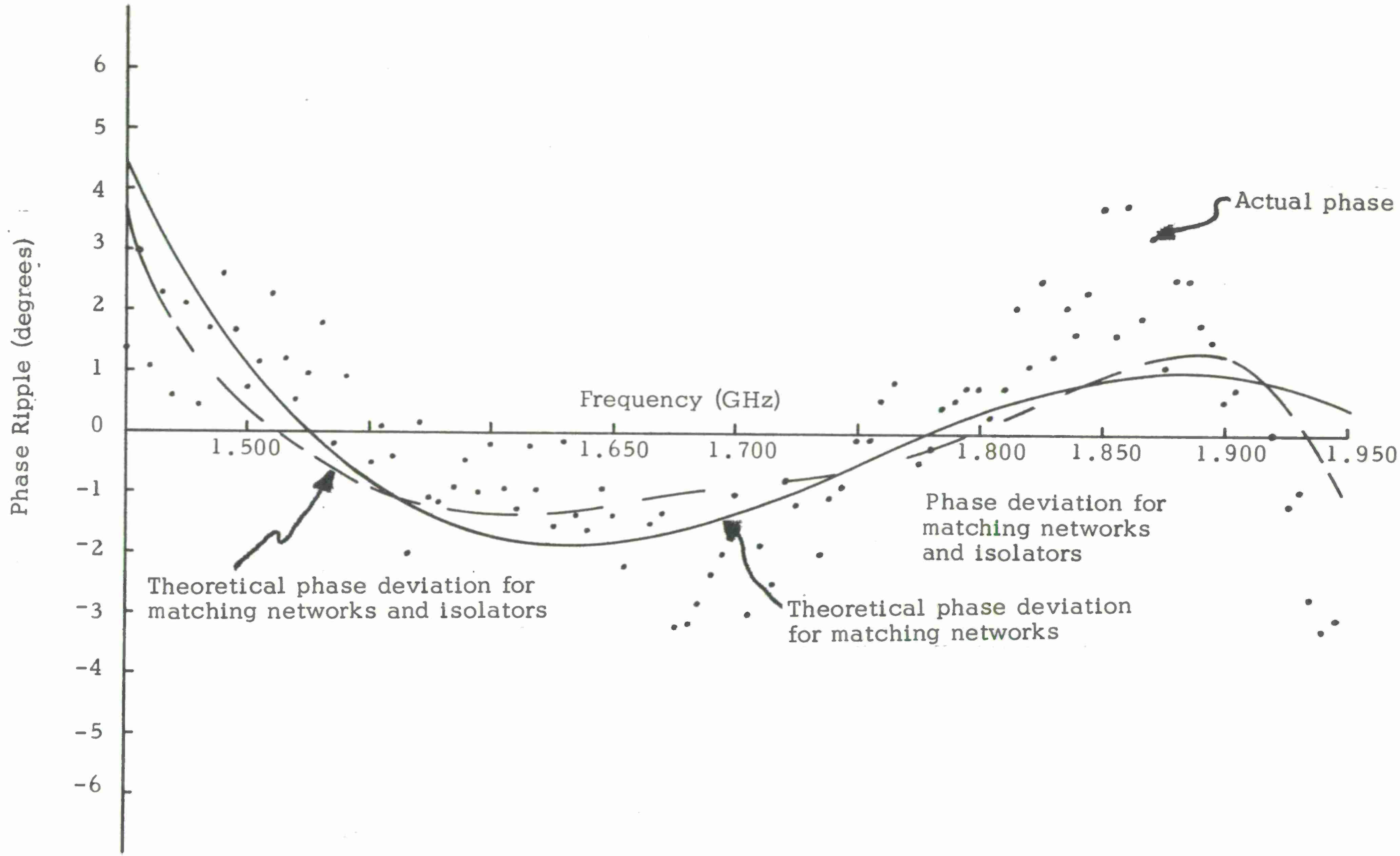

Figure 10. Comparison of theoretical phase data and phase data measured on the Hewlett Packard 8410 Network Analyzer which has a phase accuracy of 0.6 degrees.

From the previous discussion of phase ripple sources we conclude that the isolators and coupling networks are the principal sources of phase ripple in the final delay devices under discussion. This conclusion is supported by the fact that if one adds up the phase ripple measured for the isolators and calculated for the coupling networks, the sum compares quite well with the measured delay device data. This comparison is shown in Figure 10 with the dotted curve corresponding to the sum of isolator and network phase ripples. The measured ripple of just less than ±2 degrees is thus consistent with theoretical prediction.

V. DELAY STABILITY VERSUS TEMPERATURE

It was desired that a transmission phase stability of ±1 degree be maintained over a ±5°C operating temperature range. To accomplish this, it was necessary to mount the matched delay devices in a constant temperature oven since the inherent temperature stability of the delay device alone is on the order of hundreds of phase degrees/°C. A commercially available oven was selected[9] which has a factory calibrated temperature stability of 0.0028/°C. This oven is a dc proportional control oven with outside dimensions of 13.25 x 9.18 x 7.75 inches. The internal cavity is 7.30 x 11.82 x 6.00 inches. The oven capacity was much greater than was actually necessary since package size was not deemed important in this phase of the component development. The internal oven cavity maintains a cavity temperature close to 56°C when in operation. This temperature was measured at 55.84°C when operated at an ambient temperature of 26.7°C and decreased to 55.80°C when the ambient was adjusted to 12.8°C. This oven then became the external "package" for the matched delay devices with all RF connections being made via OSM connectors mounted on the oven walls. Figure 11 is a photograph of the oven with the matched pair of delay lines shown in the foreground. Figure 12 is a block diagram showing the physical component arrangement inside the constant-temperature oven.

The assembled oven "package" was tested for temperature stability in a standard electronic equipment temperature chamber which could be adjusted over a wide range around 20°C ambient. CW signals were applied to one delay device from a generator stabilized to 1 part in 10^8. The relative transmission phase was constantly monitored by the Hewlett Packard Network Analyzer. It was found that the desired ±1 degree phase stability could only be achieved for a 1°C excursion in ambient temperature above or below 20°C. Further, in a test which followed the ambient from 26°C to 16°C the transmission phase changed by 10 degrees. A considerable improvement in the over-all temperature response could be obtained by installing the present oven in a second oven or by purchasing a more stable primary oven. Although a rather bulky solution, the former would be the least expensive solution.

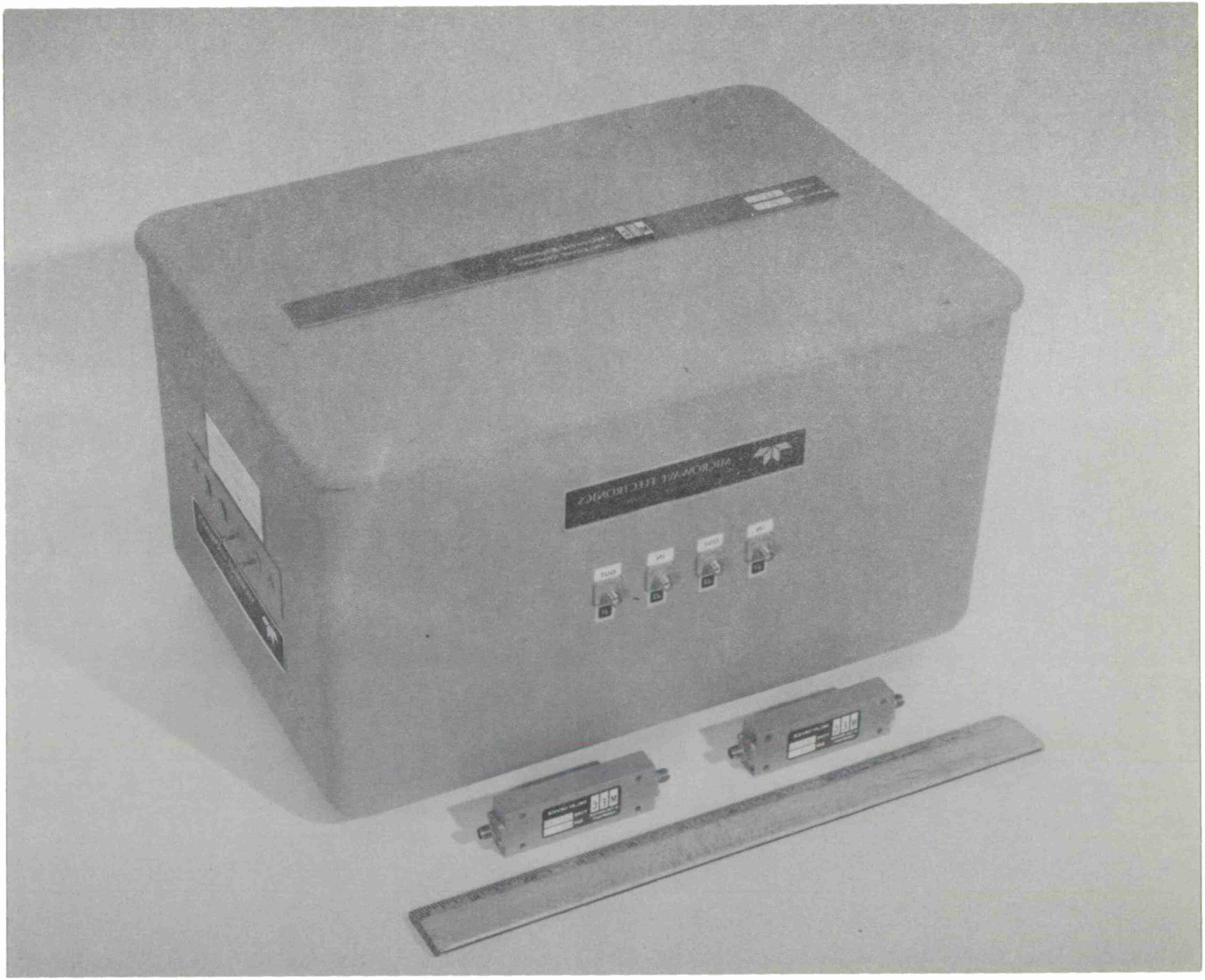

Figure 11. Matched pair delay device package.

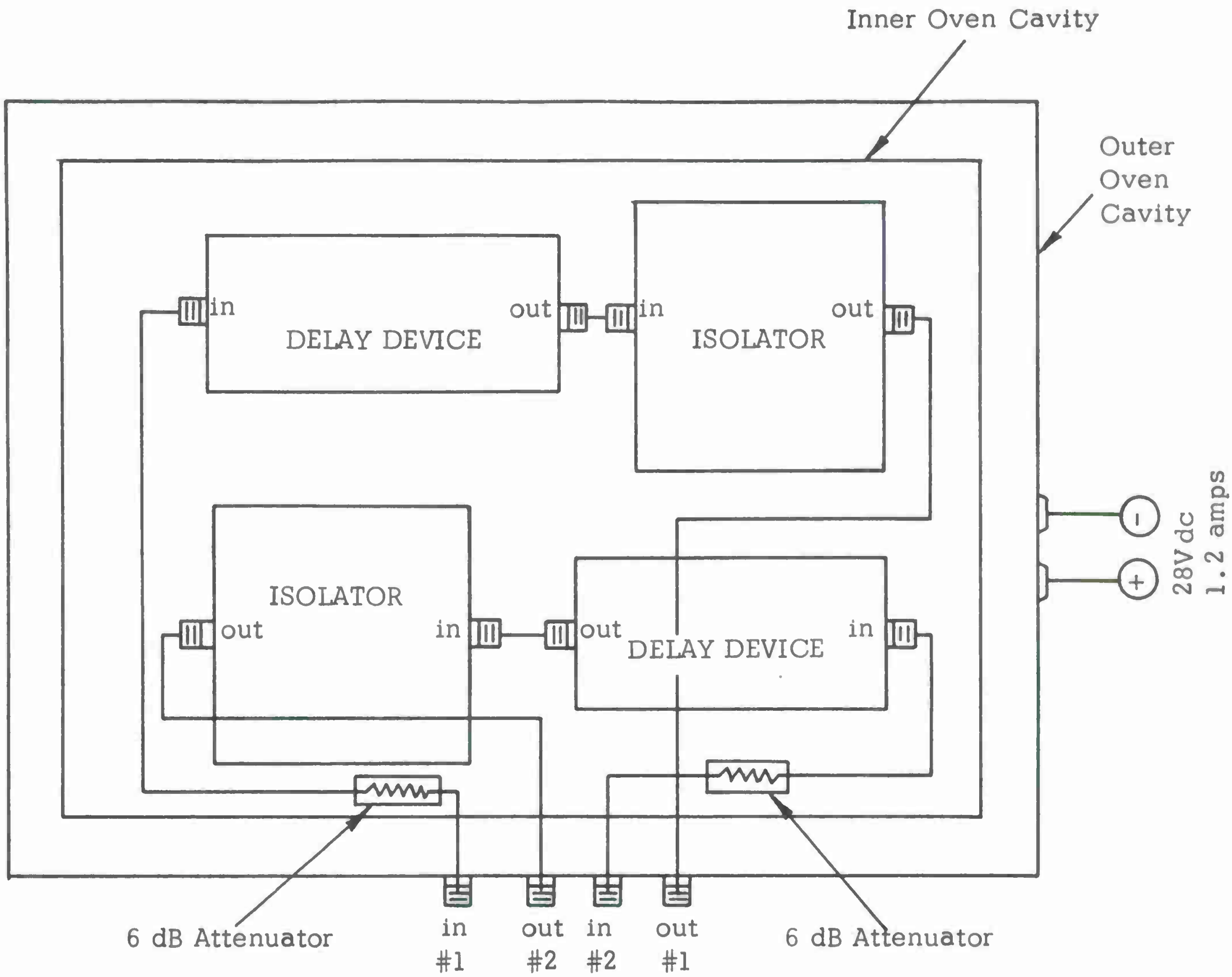

Figure 12. Component configuration inside the constant-temperature oven.

VI. FEEDTHROUGH SUPPRESSION

It was desired to obtain a feedthrough suppression of 60 dB with respect to the delayed output signal. This level of suppression was easily obtained by use of standard Teledyne MEC techniques of delay device construction. Some radiation of external cables and connectors was noticed, however, and was obviated by adding brass shielding material within the constant temperature oven.

VII. CONCLUSIONS

The purpose of this contract was to produce a pair of high-performance delay lines incorporating low loss, broad bandwidth and high triple-transit suppression characteristics. The results attained in each category have been discussed in detail. Table I is a summary of these results as compared to the design goals. This table shows that we have achieved essentially all of the original design goals. These devices combine state-of-the-art characteristics of both bandwidth and TTS, while at the same time retaining low insertion loss. Furthermore, we feel that these two devices are not the exceptions of our capability, but rather that these results can be repeated in larger quantities and at reasonable prices.

Table II is a summary of what we feel can be accomplished by adjusting available design parameters. Note that much lower insertion losses are achievable for more narrow bandwidths and when isolators rather than attenuators are used to attain low VSWR.

Table II shows that insertion losses as low as 20 dB are possible in a 4 μs delay device offering TTS levels as high as 35 dB and greater.

TABLE I

Specification	Goal	Sa 338	Sa 396
Center Frequency	1.7 GHz	1.7 GHz	1.7 GHz
Bandwidth (±0.5 dB)	500 MHz	580 MHz	620 MHz
Amplitude Ripple (500 MHz)	±0.5 dB	±0.25 dB	±0.35 dB
Phase Ripple	±2°	±2-1/2°	±2-1/2°
Delay	4 ±0.05 μsec	3.95 μsec	3.95 μsec
Delay Matching	±1 nsec	±1.5 nsec	±1.5 nsec
Insertion Loss*	30 dB	36 dB	37 dB
Triple-Travel Suppression	45 dB	>45 dB	>43 dB
Feedthrough Suppression	60 dB	> 60 dB	> 60 dB
Input and Output VSWR*	< 1.3:1	< 1.5:1	< 1.4:1
Delay Stability**	±1 electrical degree within ±5°C operating temperature	±5 electrical degrees	±5 electrical degrees

*It was noted in the original proposal stating these design goals that a compromise between insertion loss and VSWR would be necessary. The 30 dB goal could have been attained if isolators were used on both the input and outputs of each device.

** To achieve this goal a better oven is necessary.

TABLE II

4.0 μsec L-Band Delay Line Trade-Offs
for Production Quantity Delay Lines

Bandwidth (%)	Insertion Loss (±0.5 dB)	TTS	Worse Case VSWR
10	20	>35	2:1
10	23	>45	2:1
20	23	>35	4:1
20	26	>45	4:1
30	27	>35	6:1
30	30	>45	6:1

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3. W. Sperry and T. Reeder, "Matched Longitudinal Acoustic Wave Transducers", Interim Report No. 1, Contract AF19(628)-5167, May 1969.

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5. Isolators were designed and fabricated by Vector Industries, Palo Alto, Model AMF-3858.

6. The beveled face technique is further described in the W. Sperry/ T. Reeder report "Matched Longitudinal Acoustic Wave Transducers" Interim Report No. 3, Contract AF19(628)-5167, January 1970.

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8. W. Sperry and T. Reeder, "Development and Fabrication of Matched Longitudinal Acoustic Wave Transducers", Interim Report No. 2, Contract AF19(628)-5167, August 1969.

9. Oven supplied by Oven Industries, Model 3382-2.

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13. ABSTRACT

The design and fabrication of a matched pair of 4 μs, wide bandwidth delay devices is described with operation over a 500 MHz bandwidth centered at 1.7 GHz. Design techniques are discussed which allow relatively low insertion loss (35 dB) with extremely flat frequency response (±0.5 dB) and superior TTS (above 45 dB). The magnitude of transmission phase ripple relative to linear phase is considered both theoretically and experimentally. Construction in a constant-temperature oven for phase-stable operation is described. The characteristics of devices obtained in quantity production are estimated.

14. KEY WORDS

delay line
phase linear
phase stable
flat insertion loss